Dynamic Re-Crystallization of Low Carbon Steel in Plain Strain Condition

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***Abstract*—In present investigation, the study of influence of strain rate and temperature on critical stress for initiation of dynamic re-crystallization in 0.05C-1.52Cu-1.51Mn steel is studied. It was observed that critical stress for initiation of Dynamic re-crystallization (DRX) is increases initially for lower strain rate and then it become saturated at higher strain rate. It is also found that materials exhibits typical dynamic re-crystallization behaviour at higher temperature and lower strain rate. It is due to the influence of thermal energy as DRX is a thermally activated process; also at lower strain rate more time is available for nucleation and growth of strain free crystals.**

***Index Terms*—thermo-mechanical processing, dynamic re-crystallization, copper precipitation, strain rate**

I. Introduction

Grain size refinement is the only way to improve both strength and toughness simultaneously. Thermo-mechanical controlled processing is based around the concept of grain refinement. In TMCP the optimization of rolling schedule and post rolling cooling has done in order to produce the required level of grain refinement. In controlled rolling steel is finished rolled in non crystalline region, flattens the austenite grains and introduces internal defects that increases the no. of nucleation sites for ferrite. Increasing the cooling rate after rolling leads to greater under-cooling, this produces higher nucleation density. The grain size of 5-10 µm is achieved by using the approach stated above. However it is possible to further refine the microstructure due to higher cooling rate. In this case microstructure has much higher internal dislocation density [1]-[5]. The final microstructure and properties of steel are governed by hot rolling. The hot rolling is capable of producing uniformity in its properties and in microstructure as well [6]. Low carbon steel (carbon% 0.15 to 0.05) is one of the most common steel used in sheet metals due to its malleability; as its carbon content is lower, it is neither extremely brittle nor ductile. In this kind of steel transition of austenite phase usually takes place during cooling on the output roller after hot rolling. The reduction of carbon content improves toughness and weldability in steel but its strength is decreases. It is reported that addition of copper takes care of reduction in strength, because copper is known to provide precipitation strengthening in steel. It is found that addition of Cu up to 0.8% leads to improvement its strength significantly through precipitation hardening [7]. Hornbogen *et al.* in 1960 studied the Cu precipitation behavior in iron and discussed relation between tensile property and the sequence of Cu clusters, precipitation and coarsening [8]-[10].

Dynamic re-crystallization is one of the most important methods of grain refinement in steels. It is defined as the process in which nucleation as well as growth (grain boundary migration) takes place during straining [11]-[12]. The flow curve is the characteristic of DRX phenomena; it gives the idea of grain refinement during the process. The ‘single peak’ flow curve is associated with grain refinement while ‘cyclic curve’ indicates grain coarsening. The DRX depend upon various physical parameters like strain (ε), strain rate ($\dot{\varepsilon}$), temperature and prior grain size [13]-[14]. The point at which the combine effect of strain hardening and recovery are unable to accommodate more immobile dislocation is the starting point of DRX process. In

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materials like steel the DRX can initiate at a critical condition of stress accumulation as the kinetics of dynamic recovery is low for austenitic phase [15]. In present investigation the critical stress required to start DRX is calculated for 0.05C-1.52Cu-1.51Mn steel and the influence of strain rate and temperature is studied.

II. Experimental Route

The material under investigation is 0.05C-1.52Cu-1.51Mn steel. The chemical composition is shown in Table I. Thermo-mechanical simulator (Gleeble) was used for hot compression test in plain strain condition. The specimens were austenitized at 1100^{o}C for 5 min and cooled at the rate of 5^{o}C/Sec; it is then subjected to hot compression as shown in Fig. 1. Single hit hot compression tests were conducted at temperature 850-1000^{o}C with strain rates of 0.01, 0.1, 1 s^{-1}.

TABLE I. Chemical Composition of Steel

Element	C	Si	Mn	P	S	Cu	B	Ti
Wt %	0.05	0.02	1.51	0.013	0.011	1.52	0.001	0.06

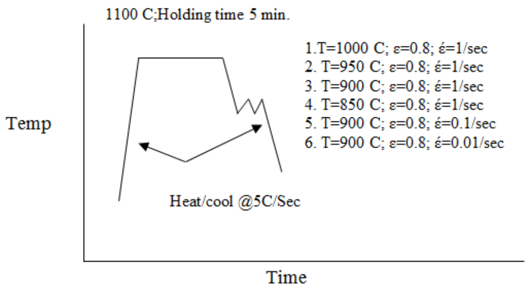

Figure 1. Thermo-Mechanical process used in experiments

III. Results and Discussion

(Fig. 2-Fig. 7) shows flow curves at different temperature and strain rate. The specimens at low strain rate or high temperature show typical DRX behaviour (Fig. 2, Fig. 6, and Fig. 7). It is may be due to the availability of time for nucleation and growth and influence of thermal energy. The Θ-σ analysis is used to calculate critical stress for initiation of DRX [15]. It is found that this critical stress increases initially at lower strain rate and intended towards saturation for higher strain rate (Fig. 9). However as the deformation temperature increases; the critical stress for initiation of DRX decreases and becomes independent at higher deformation temperature (Fig. 10).

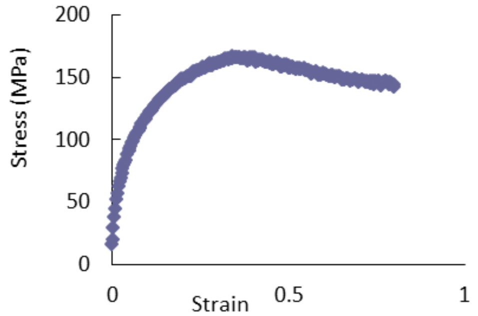

Figure 2. Flow curve at T=1000C, ε=0.8, έ=1/s

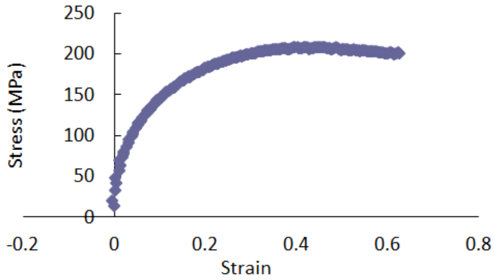

Figure 3. Flow curve at T=950C; ε=0.8;έ=1/sec

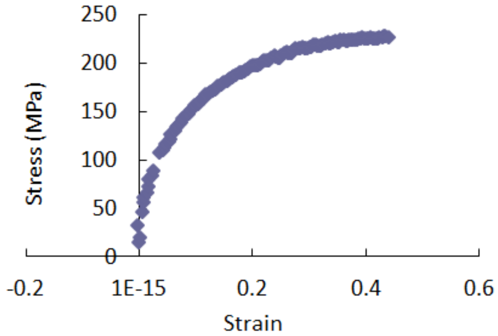

Figure 4. Flow curve at T=900 ^{o}C; ε=0.8;έ=1/s

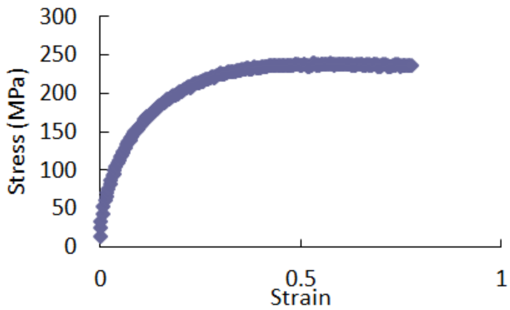

Figure 5. Flow curve at T=850 ^{o}C;ε=0.8;έ=1/sec

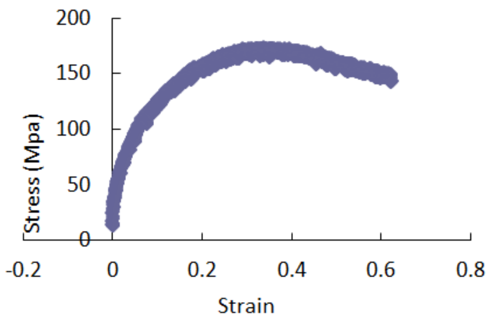

Figure 6. Flow curve at T=900 ^{o}C; ε=0.8;έ=0.1/sec

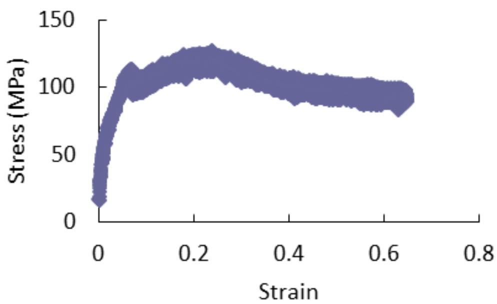

Figure 7. Flow curve at T=900^{o}C;ε=0.8;έ=0.01/sec

A. *The Θ-Σ Analysis to Calculate Critical Stress for Initiation of DRX:*

From true stress/ true strain Curve; plot of work hardening rate Vs true stress (ϴ-σ) is given in Fig. 8 as:

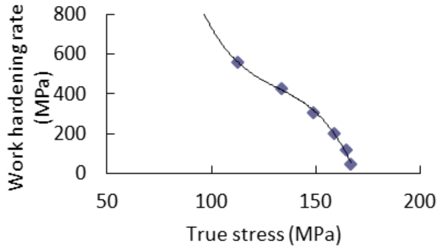

Figure 8. Work hardening rate Vs True stress

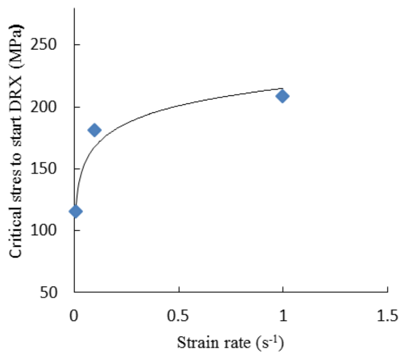

Figure 9. Critical stress to start DRX Vs Strain rate

The inflection point is detected by fitting 3rd degree polynomial to ϴ-σ curve

$$\Theta = A\sigma^3 + B\sigma^2 + C\sigma + D \tag{1}$$

At critical stress for initiation of DRX the second derivative becomes zero; so

$$\frac{d^2\Theta}{d^2\sigma} = 6A\sigma + 2B \tag{2}$$

Becomes zero; therefore; σ (critical) = -B/3A (3)

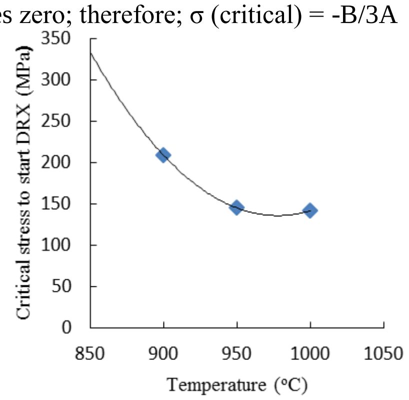

Figure 10. Critical stress to start DRX Vs Temp.

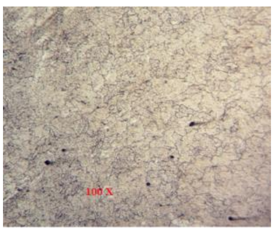

Figure 11. Optical image

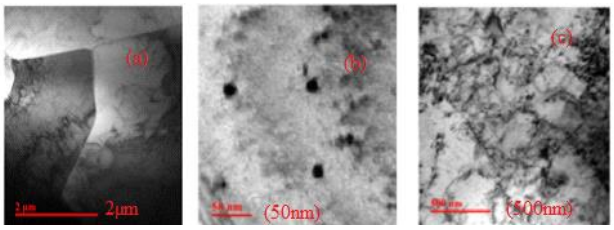

Figure 12. (a), (b), (c) TEM images

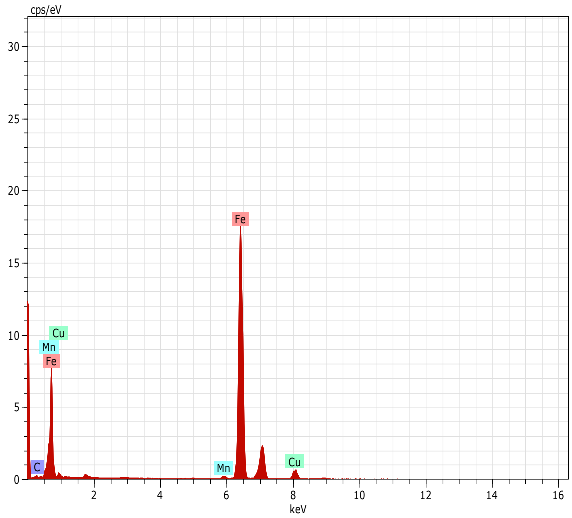

Figure 13. EDX image

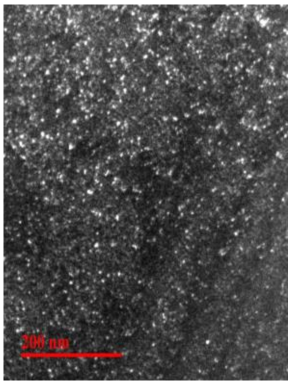

Figure 14. Dark field (TEM)

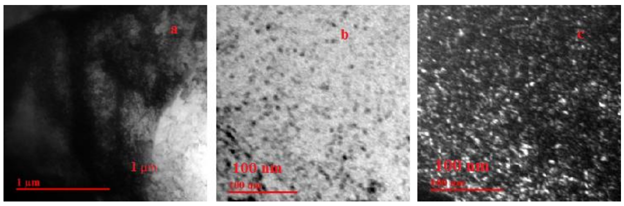

Figure 15. (a), (b) (c) TEM images

Optical microscopy image is shown in Fig. 11 for specimen deformed at 900°C and strain rate of 0.01 s^{-1}; the image shows a few eqi-axed fine grains which is indication of dynamic re-crystallization. For specimen deformed at 1000°C and at strain rate 1 s^{-1}; TEM image shows large angle boundary with sub-grain boundary inside. It is seem that grain size of 5-6 µm (Fig. 12.a). The precipitates of Cu can be seen in Fig. 12.b, 13 and 14.

However there is no DRX at deformation temperature 900°C and strain rate 1 s^{-1}; There is sub-boundary precipitation of Cu and DRX took place as shown in Fig. 12.c. The TEM image in Fig 15 (a) for the specimen deformed at 900°C and strain rate 1 s^{-1} shows elongated grains which indicates no dynamic re-crystallization to take place. Fig 15 (b) shows a few precipitates of Cu; however Fig. 15 (c) which is a dark field images confirms it is the precipitates of Cu. It is reported that addition of copper takes care of reduction in strength, because copper is known to provide precipitation strengthening in steel. It is found that addition of Cu up to leads to improvement its strength significantly through precipitation hardening [16]. It is felt that the study of interaction of Cu precipitates and dislocation introduced by deformation will be required for better understanding of precipitation behavior of Cu and its effect on grain refinement/improvement in strength.

IV. Conclusion

1. DRX of austenite takes places at lower strain rates.
2. Critical stress for DRX of austenite decreases with strain rate; critical stress value saturates at 1000C with strain rate 1/sec.
3. It is hinted that Cu precipitation take place process adopted in the experiments

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